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DESIGN PARAMETERS FOR A GYRO-TWA OPERATING AT THE SECOND CYCLOT--ETC(U)
MAY 79 K R CHU, V L GRANATSTEIN, A T DROBOT   MIPR-FY7619-70026

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NRL Memorandum Report 3950

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Design Parameters for a Gyro-TWA Operating at the Second Cyclotron Harmonic

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and

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Designs for a 10 GHz gyrotron travelling wave amplifier are made on the basis of recent gyrotron theory. The amplifier operates on the TE_{01} waveguide mode at the second electron cyclotron harmonic frequency. Although the designs are for specific systems, the design procedures as well as the trend shown in the various design options are of general interest. sub 01		

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In a recent report[1], we presented analytical and simulation studies of the gyrotron travelling wave amplifier (gyro-TWA) operating on the TE_{on} mode where n is the radial eigenmode number of a wave in a cylindrical waveguide) at a harmonic of the electron cyclotron frequency. In the present report, we shall apply the theory and techniques developed in Ref. 1 to design a 10 GHz gyro-TWA operating on the TE_{o1} mode and at the second cyclotron harmonic. The design is subject to the restriction that the electron gun to be used has fixed dimensions.

Following the notations of Ref. 1, we outline, step by step, the procedures used for the present design.

(1) Determining the beam frame wave number $\bar{k}_z'$.

In general the waveguide characteristic curve intersects with the beam characteristic curve at two points in the $\bar{\omega}' - \bar{k}_z'$ plane. One point corresponds to the operating mode, a forward wave, while the other point corresponds to a backward wave which may cause oscillations. In order to eliminate the backward wave, we have chosen $\bar{k}_z' = 0$ so that the two curves intersect at only one point (i.e. at a grazing angle, see Fig. 4 of Ref. 1).

(2) Determining the beam electron guiding center position with respect to the waveguide wall.

It is shown in Ref. 1 that for n = 1 and s = 2, the optimum choice for $\bar{r}_o$ is $\bar{r}_o = 0.8$. Here, however, the fixed electron gun dimensions have necessitated a choice of $\bar{r}_o = 0.48$. From Eq. (50) of Ref. 1, we estimate that the efficiency for $\bar{r}_o = 0.48$ will be approximately 75% of that for the optimum $\bar{r}_o$.

Note: Manuscript submitted March 22, 1979.

(3) Determining the beam density parameter ν.

Considering the operating voltage and current of the electron gun, we have fixed ν at two values, i.e., $\nu = 1.5 \times 10^{-3}$ and $\nu = 2 \times 10^{-3}$.

(4) Determining the magnetic field fine tuning parameter X' ($\propto B_o$).

By choosing the wave number $\bar{k}_z' = 0$, we have already specified a magnetic field corresponding to a grazing or near grazing intersection between the beam characteristic curve and the waveguide characteristic curve (see Fig. 4 of Ref. 1). It is shown in Ref. 1 that $X' = 1$ (exact grazing intersection) gives the larger bandwidth and power gain per unit distance, while $X' = X_h'$ (near grazing intersection) gives a higher efficiency, where X_h', a parameter near unity, corresponds to the magnetic field which gives half the growth rate as compared with $X' = 1$. For maximum flexibility, we shall present design options based on either choice of X'.

(5) Evaluating the beam frame efficiency η' as a function of the beam energy W_b'.

This was done with our numerical simulation code. Fig. 1 shows the η' vs. W_b' curves for the chosen values of ν' and X_h'. In Fig. 1, 24 data points have been numbered. These are the points to be converted into experimental designs.

(6) Calculating the properties of the designed systems.

For each data point marked on Fig. 1, we calculate the corresponding bandwidth, power gain, and tolerance to the beam energy and axial velocity spreads, etc., on the basis of the dispersion relation [Eq. (18) of Ref. 1]. Fig. 2 shows a typical plot of the growth rate $\overline{W}$ versus $\bar{k}_z$ (in lab frame) for a 60 kV, 7 Amp beam with $V_{\perp o}/V_{zo} = 2$. Bandwidth and power gain/unit length

can be derived from this figure. Note that the unstable spectrum is restricted in the positive $\bar{k}_z'$ region. This is also the case for all the data points shown in Fig. 1.

(7) Converting the beam frame normalized design data into lab frame physical design parameters.

Table IV of Ref. 1 has been used to convert the data points marked on Fig. 1 into actual design parameters. In carrying out the conversion, we have assumed a waveguide wall radius of 1.842 cm to be consistent with the desired 10 GHz wave frequency and we have used three values of α ($\equiv V_{\perp o}/V_{zo}$), i.e., α = 2.0, 1.5, and 1.0.

The final designs can be divided into two categories - optimum bandwidth ($X' = 1$) and optimum efficiency ($X' = X_h'$). Tables I through III list the design parameters in the former category, while Table IV through VI list the design parameters in the second category. In each category, three optional values of α have been given, each generating a separate table. In each table, there are six optional designs for various values of beam voltage and current. Note that all the designs have the same waveguide radius (1.842 cm or 0.725 inch), but the wave frequencies are slightly different because of the difference in beam parameters and applied magnetic fields. Generally speaking, for the same beam used, optimum efficiency operation gives an efficiency higher than that of the optimum bandwidth operation by a factor of ~ 1.5, but it gives a bandwidth and power gain/unit length lower than those of the optimum bandwidth operation by a factor of ~ 3.5 and ~ 2, respectively. One can change from optimum efficiency operation to optimum bandwidth operation or vice versa by fine tuning the magnetic field and the driver frequency according to the design specifications. In order to reach

a 20 dB total power gain, an interaction length of 30-140 cm is required depending on which design option is used. The upper bound conditions on the beam energy and axial velocity spreads [the last two numbers in the design, cf. Eq. (53) of Ref. 1] indicate that the allowable beam energy spread and the allowable beam axial velocity spread are greater for larger α and $X' = X_h'$ than for smaller α and $X' = 1$. To achieve the design performance when $\alpha = 2$ and $X' = X_h'$, one requires $\Delta V_z/V_{zo} \ll 50\%$ and $\Delta W_b'/W_b' \ll 20\%$, while for $\alpha = 1$ and $X' = 1$, the requirement is $\Delta V_z/V_{zo} \ll 8\%$ and $\Delta W_b/W_b \ll 8\%$.

REFERENCE

1. K. R. Chu and A. T. Drobot, "Theory and Single Wave Simulation of the Gyrotron Travelling Wave Amplifier Operating at Cyclotron Harmonics," Naval Research Laboratory, Memo Report 3788 (1978, to be published).

TABLE I - Design Parameters for $X' = 1$, $\alpha = 2$.

data no.	4	5	6	10	11	12
V(kV)	49.54	55.68	61.80	49.54	55.68	61.80
I (Amp)	4.83	5.09	5.33	6.44	6.79	7.11
Wave frequency (GH_z)	10.15	10.17	10.19	10.15	10.17	10.19
Efficiency (%)	10.40	9.98	9.58	11.35	10.88	10.45
Beam power (kW)	239.58	283.64	329.64	319.44	378.19	439.52
Wave power (kW)	24.92	28.32	31.59	36.27	41.16	45.94
Magnetic field (kG)	1.91	1.93	1.95	1.91	1.93	1.95
Wall radius (cm)	1.842	1.842	1.842	1.842	1.842	1.842
Larmor radius (cm)	0.363	0.383	0.401	0.363	0.383	0.401
Inner radius (cm)	0.521	0.502	0.484	0.521	0.502	0.484
Avg. beam radius (cm)	0.884	0.884	0.884	0.884	0.884	0.884
Outer radius (cm)	1.247	1.267	1.285	1.247	1.267	1.285
k_z (cm^{-1})	0.39	0.41	0.43	0.39	0.41	0.43
$V_{\perp o}/C$	0.37	0.39	0.40	0.37	0.39	0.40
V_{zo}/C	0.18	0.19	0.20	0.18	0.19	0.20
e-fold time (nsec)	2.66	2.50	2.36	2.45	2.29	2.17
power gain (dB/cm)	0.58	0.59	0.60	0.63	0.64	0.65
20 dB gain bandwidth	0.043	0.046	0.049	0.044	0.048	0.051
$\Delta V_z/V_{zo} \ll$	0.23	0.22	0.21	0.26	0.25	0.24
$\Delta W_b/W_{bo} \ll$	0.09	0.09	0.08	0.10	0.10	0.09

TABLE II - Design Parameters for $X' = 1$, $\alpha = 1.5$

data no.	3	4	5	9	10	11
v(kV)	49.84	56.85	63.84	49.84	56.85	63.84
I (Amp)	6.07	6.44	6.79	8.09	8.59	9.05
Wave frequency (GHz)	10.24	10.28	10.32	10.25	10.29	10.32
Efficiency (%)	9.59	9.18	8.83	10.46	10.02	9.63
Beam power (kW)	302.67	366.58	433.67	403.56	488.78	578.22
Wave power (kW)	29.05	33.67	38.32	42.23	49.00	55.69
Magnetic field (kG)	1.90	1.91	1.93	1.90	1.91	1.93
Wall radius (cm)	1.842	1.842	1.842	1.842	1.842	1.842
Larmor radius (cm)	0.342	0.363	0.383	0.342	0.363	0.383
Inner radius (cm)	0.542	0.521	0.502	0.542	0.521	0.502
Avg. beam radius (cm)	0.884	0.884	0.884	0.884	0.884	0.884
Outer radius (cm)	1.226	1.247	1.267	1.226	1.247	1.267
k_z (cm^{-1})	0.49	0.52	0.55	0.49	0.52	0.55
$V_{\perp o}/C$	0.34	0.36	0.38	0.34	0.36	0.38
V_{zo}/C	0.23	0.24	0.25	0.23	0.24	0.25
e-fold time (nsec)	2.91	2.70	2.53	2.67	2.48	2.33
power gain (dB/cm)	0.43	0.43	0.44	0.46	0.47	0.48
20 dB gain bandwidth	0.051	0.056	0.060	0.050	0.057	0.063
$\Delta V_z/V_{zo} \ll$	0.14	0.13	0.12	0.16	0.15	0.14
$\Delta W_b/W_{bo} \ll$	0.08	0.08	0.08	0.10	0.09	0.08

TABLE III - Design Parameters for $X' = 1$, $\alpha = 1$

data no.	1	2	3	7	8	9
V(kV)	48.86	58.39	67.84	48.86	58.39	67.84
I (Amp)	7.80	8.49	9.10	10.41	11.32	12.14
Wave frequency (GHz)	10.42	10.50	10.58	10.42	10.50	10.59
Efficiency (%)	8.02	7.63	7.28	8.77	8.33	7.93
Beam power (kW)	381.49	495.88	618.03	508.65	661.17	824.04
Wave power (kW)	30.60	37.84	45.00	44.62	55.11	65.42
Magnetic field (kG)	1.86	1.88	1.90	1.86	1.88	1.90
Wall radius (cm)	1.842	1.842	1.842	1.842	1.842	1.842
Larmor radius (cm)	0.293	0.319	0.342	0.293	0.319	0.342
Inner radius (cm)	0.591	0.565	0.542	0.591	0.565	0.542
Avg. beam radius (cm)	0.884	0.884	0.884	0.884	0.884	0.884
Outer radius (cm)	1.177	1.203	1.226	1.177	1.203	1.226
k_z (cm^{-1})	0.63	0.69	0.74	0.63	0.69	0.74
$V_{\perp o}/C$	0.29	0.31	0.33	0.29	0.31	0.33
V_{zo}/C	0.29	0.31	0.33	0.29	0.31	0.33
e-fold time (nsec)	3.63	3.27	3.00	3.35	3.01	2.76
power gain (dB/cm)	0.27	0.28	0.28	0.29	0.30	0.31
20 dB gain bandwidth	0.056	0.066	0.073	0.059	0.067	0.075
$\Delta V_z/V_{zo} \ll$	0.07	0.06	0.06	0.08	0.07	0.07
$\Delta W_b/W_{bo} \ll$	0.07	0.07	0.06	0.08	0.08	0.07

TABLE IV - Design Parameters for $X' = X_h'$, $\alpha = 2$

data no.	16	17	18	22	23	24
V(kV)	49.54	55.68	61.80	49.54	55.68	61.80
I (Amp)	4.83	5.09	5.33	6.44	6.79	7.11
Wave frequency (GH_z)	10.08	10.09	10.11	10.07	10.09	10.11
Efficiency (%)	24.97	24.06	22.80	27.03	25.62	24.79
Beam power (kW)	239.58	283.64	329.64	319.44	378.19	439.52
Wave power (kW)	59.84	68.24	75.18	86.35	96.92	108.96
Magnetic field (kG)	1.89	1.91	1.92	1.89	1.91	1.92
Wall radius (cm)	1.842	1.842	1.842	1.842	1.842	1.842
Larmor radius (cm)	0.367	0.387	0.406	0.368	0.388	0.406
Inner radius (cm)	0.517	0.497	0.479	0.517	0.497	0.478
Avg. beam radius (cm)	0.884	0.884	0.884	0.884	0.884	0.884
Outer radius (cm)	1.251	1.271	1.290	1.252	1.272	1.290
k_z (cm^{-1})	0.39	0.41	0.43	0.39	0.41	0.43
$V_{\perp o}/C$	0.37	0.39	0.40	0.37	0.39	0.40
V_{zo}/C	0.18	0.19	0.20	0.18	0.19	0.20
e-fold time (nsec)	5.31	4.98	4.68	4.88	4.60	4.34
power gain (dB/cm)	0.29	0.29	0.30	0.32	0.32	0.32
20 dB gain bandwidth	0.012	0.013	0.014	0.013	0.013	0.014
$\Delta V_z/V_{zo} <<$	0.48	0.46	0.44	0.51	0.49	0.48
$\Delta W_b/W_{bo} <<$	0.19	0.18	0.17	0.20	0.19	0.19

TABLE V - Design Parameters for $X' = X'_h$, $\alpha = 1.5$

data no.	15	16	17	21	22	23
V(kV)	49.84	56.85	63.84	49.84	56.85	63.84
I (Amp)	6.07	6.44	6.79	8.09	8.59	9.05
Wave frequency (GH_z)	10.18	10.21	10.24	10.18	10.21	10.24
Efficiency (%)	23.09	22.05	21.29	24.53	23.86	22.67
Beam power (kW)	302.67	366.58	433.67	403.56	488.78	578.22
Wave power (kW)	69.90	80.85	92.33	99.02	116.66	131.12
Magnetic field (kG)	1.88	1.89	1.91	1.87	1.89	1.91
Wall radius (cm)	1.842	1.842	1.842	1.842	1.842	1.842
Larmor radius (cm)	0.346	0.367	0.387	0.346	0.368	0.388
Inner radius (cm)	0.539	0.517	0.497	0.538	0.517	0.497
Avg.beam radius (cm)	0.884	0.884	0.884	0.884	0.884	0.884
Outer radius (cm)	1.230	1.251	1.271	1.230	1.252	1.272
k_z (cm^{-1})	0.49	0.52	0.55	0.49	0.52	0.55
$V_{\perp o}/C$	0.34	0.36	0.38	0.34	0.36	0.38
V_{zo}/C	0.23	0.24	0.25	0.23	0.24	0.25
e-fold time (nsec)	5.74	5.38	5.06	5.27	4.95	4.66
power gain (dB/cm)	0.21	0.22	0.22	0.23	0.24	0.24
20 dB gain bandwidth	0.014	0.016	0.017	0.015	0.017	0.017
$\Delta V_z/V_{zo} \ll$	0.28	0.27	0.26	0.31	0.29	0.28
$\Delta W_b/W_{bo} \ll$	0.17	0.17	0.16	0.19	0.18	0.17

TABLE VI - Design Parameters for $X' = X_h', \alpha = 1$

data no.	13	14	15	19	20	21
V(kV)	48.86	58.39	67.84	48.86	58.39	67.84
I (Amp)	7.80	8.49	9.10	10.41	11.32	12.14
Wave frequency (GH_z)	10.36	10.44	10.51	10.36	10.44	10.51
Efficiency (%)	18.93	18.13	17.52	20.38	19.54	18.61
Beam power (kW)	381.49	495.88	618.03	508.65	661.17	824.04
Wave power (kW)	72.23	89.92	108.28	103.66	129.20	153.40
Magnetic field (kG)	1.84	1.86	1.88	1.84	1.86	1.87
Wall radius (cm)	1.842	1.842	1.842	1.842	1.842	1.842
Larmor radius (cm)	0.296	0.322	0.346	0.296	0.322	0.346
Inner radius (cm)	0.589	0.562	0.539	0.588	0.562	0.538
Avg. beam radius (cm)	0.884	0.884	0.884	0.884	0.884	0.884
Outer radius (cm)	1.180	1.206	1.230	1.180	1.206	1.230
k_z (cm^{-1})	0.63	0.68	0.73	0.63	0.68	0.73
$V_{\perp o}/C$	0.29	0.31	0.33	0.29	0.31	0.33
V_{zo}/C	0.29	0.31	0.33	0.29	0.31	0.33
e-fold time (nsec)	7.14	6.54	5.93	7.01	6.00	5.44
Power gain (dB/cm)	0.13	0.14	0.14	0.14	0.15	0.15
20 dB gain bandwidth	0.017	0.019	0.021	0.016	0.020	0.022
$\Delta V_z/V_{zo} <<$	0.13	0.13	0.12	0.15	0.14	0.13
$\Delta W_b/W_{bo} <<$	0.14	0.14	0.13	0.16	0.15	0.14

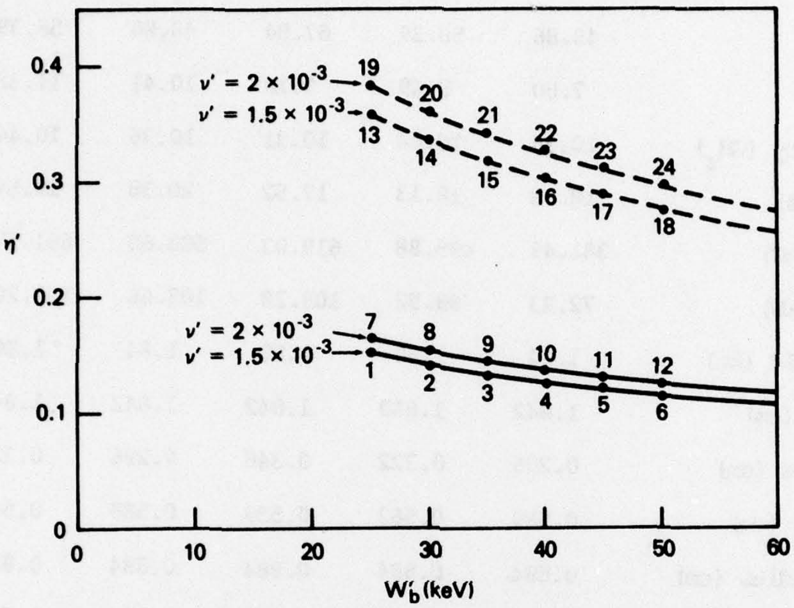

Fig. 1 - Beam frame efficiency η' versus beam energy W_b'. Solid curves are for $X' = 1$ and dashed curves are for $X' = X_h'$.

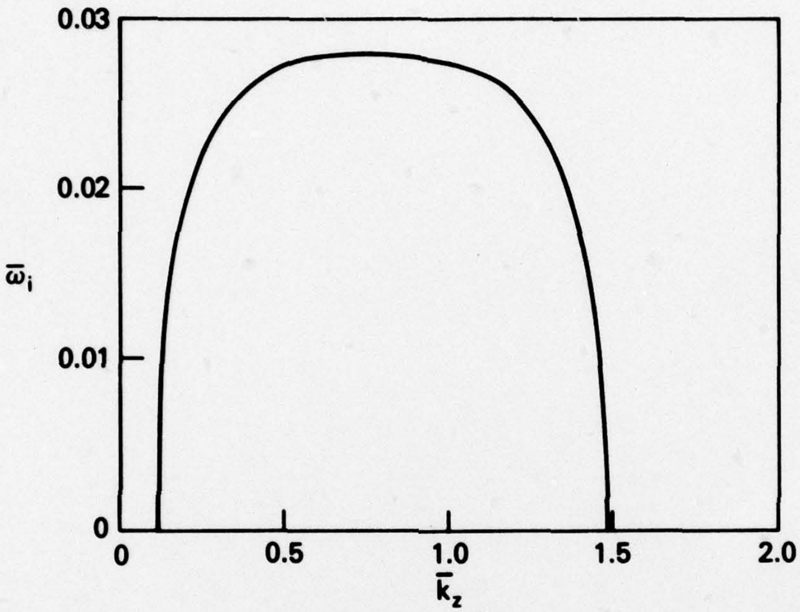

Fig. 2 - Lab frame growth rate $\bar{W}_i$ versus wave number $\bar{k}_z$ for a 60 kV, 7 Amp electron beam with $V_{\perp o}/V_{zo} = 2$.